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Reinjection in geothermal fields: A review of worldwide experience

Eylem Kaya *, Sadiq J. Zarrouk, Michael J. O'Sullivan

Department of Engineering Science, University of Auckland, Private Bag 92019, Auckland 1142, New Zealand

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ABSTRACT

The worldwide experience of reinjection in geothermal fields is reviewed. Information from 91 electric-power producing geothermal fields shows that: a reinjection plan should be developed as early as possible in field development and it should be flexible as it is likely to change with time. The optimum reinjection strategy depends on the type of geothermal system. For vapour-dominated systems which can run out of water reinjection should be infield. While for hot water and liquid-dominated two-phase systems (low-enthalpy and medium-enthalpy) reinjection is likely to involve a mix of infield and outfield injection. In general infield reinjection provides pressure support and thus reduces drawdown and the potential for subsidence, whereas outfield reinjection reduces the risk of cold water returning to the production area. Deep reinjection reduces the risk of groundwater contamination and ground surface inflation. The proportion of infield to outfield reinjection and the location (deep or shallow) is case specific and typically the infield reinjection rate will vary with time as part of the steam field management strategy.

Contents

1. Introduction

1.1. Background

Reinjection is a very important part of any geothermal development and it may become the key factor in the success or failure of the field. Reinjection started as a method of waste water disposal [1–3], but now it has become an important tool for field management. It is a key issue which can be controversial [1]. It should be dealt with early in the development by deciding whether to inject infield or outfield, deep or shallow, or possibly some combination of all of these options.

In many new fields the common practice is to convert poor producers or shallow investigation wells into reinjection wells (e.g. Matsukawa [4], Wairakei [5], Olkaria [6]). This practice has resulted in delays in connecting the power station to the grid or

* Corresponding author. Tel.: +64 9 373 7599x87490; fax: +64 9 373 7468.
E-mail address: e.kaya@auckland.ac.nz (E. Kaya).

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having it reach full generation capacity because reinjection capacity is limited or injectivity reduces with time. In few extreme cases, lack of injection capacity resulting from this policy has necessitated permanent reduction to production levels after the construction of the power station [2]. Reinjection returns are a common problem in most of these fields, and have often required the relocation of reinjection wells (e.g. Tiwi [7], Ahuachapan [8], Miravalles [9], Hatchobaru [3,10], Uenotai [11], Bulalo [12]) and have sometimes resulted in a disruption to field operations (e.g. Tiwi [7], Mori [13], Kakkonda [14]).

The reinjected water inevitably flows in the direction of the high hydraulic pressure gradient established between the injection and production wells. This may occur quite quickly if good fracture permeability connects the production and injection areas. As the reinjected water moves from the injection area to the production area it extracts heat from the rock matrix and a chemical signature can be detected well ahead of the cooling effects, i.e. the arrival of the thermal front. In two-phase production zones thermal breakthrough results in a slowing down in the boiling rate [15] and thus a reduction in the production enthalpy. Thermal breakthrough leads to a number of operational problems including: the power plant running below design capacity, the need for make-up wells and modifications to field operations [16].

Each field has a different response to a particular reinjection strategy and a sound monitoring plan needs to be in place to provide early warning and to help in formulating an appropriate steam field management strategy [9,17].

Reinjection has the following advantages [2]:

- It is an environmentally friendly method for the disposal of separated geothermal brine and steam condensate, especially when compared with surface discharge of waste geothermal fluid, which can results in thermal and chemical pollution of shallow ground water and water ways.
- Reinjection may help with the recharge of the reservoir and may provide pressure support, thus reducing reservoir pressure drawdown and preventing cold water infiltration.
- Reinjection also helps in reducing and managing subsidence that can arise from large scale fluid withdrawal.
- Reinjection provides the reservoir with low-gas working fluid compared to the higher gas content in the natural deep fluid. This can result in improved plant efficiency with less gas in the geothermal steam going through the turbines.

Reinjection also has the following disadvantages and difficulties [2]:

- Difficulty and expense of siting suitable reinjection wells.
- Cooling of the production zones and quenching of steam wells.
- Dealing with large reinjection pressures.
- Groundwater contamination and leakage of reinjected fluid to the surface.
- Ground inflation.
- Change of chemistry in production wells. For example a change in chloride concentration and pH will change the solubility of solids and may trigger corrosion or scaling.
- Induced seismic activity.

The design of an injection strategy for a geothermal system is a complex problem and several parameters need to be considered [3], for example: disposal of waste fluid, cost, reservoir temperature – thermal breakthrough, reservoir pressure – production decline, temperature of injected fluid, silica scaling, chemistry changes in reservoir fluid, subsidence and the selection of injection locations.

This survey covers fields that are currently generating electricity, but does not include direct use applications. Various past and current reinjection strategies practiced in these geothermal fields and the responses of different type of geothermal reservoirs to these strategies are discussed below.

1.2. Classification of geothermal systems

The effect of reinjection on production depends on the structure of the individual system but there are generic differences depending on the thermodynamic state, geological structure and hydrological setting. To provide an optimum reinjection plan, geothermal systems should be evaluated according to their individual characteristics. In this paper, to assist with the evaluation of reinjection effects, geothermal reservoirs are classified into five groups, based on the representative characteristics of each reservoir. The criteria used for defining these categories are shown in Table 1. However they are not rigid criteria. For example some wells in medium-enthalpy systems may have production enthalpies greater than 1500 kJ/kg. Similarly within a single geothermal system there may be distinct zones of different types. For example at Wairakei there is a shallow vapour-dominated zone in a predominantly low-enthalpy, two-phase, liquid-dominated system.

The general characteristics of each type of geothermal systems given in are summarized below.

1.2.1. Hot-water systems

In these systems no boiling occurs before or after production commences. Thus large pressure gradients must be set up to move fluid towards the production wells. Without any injection the pressure will continue to decline until the induced recharge from above, below and laterally matches the overall production rate. In many cases, without injection, the pressure will drop too low to allow the production wells to continue operation. Injection assists by providing extra mass and by boosting pressures. From this perspective, it is desirable to have infield injection, with injection wells close to production wells, in such systems. However, there is a fundamental tension between this beneficial pressure maintenance effect and thermal breakthrough (when the cool injected water reaches the production wells). In some fields, particularly those with a few large faults, thermal breakthrough has occurred rapidly and injection has been moved further out, e.g. Brady, USA [18].

1.2.2. Two-phase, liquid-dominated, low-enthalpy systems

These systems are quite similar to the medium-enthalpy systems discussed below, except for their permeability. Low-enthalpy systems are typically much more generally fractured with larger permeability. Thus when production begins, the

Table 1
Categories of geothermal systems.

Category		Temperature (T)	Production enthalpy (h)
Hot-water		$T < 220\,^{\circ}C$	$h < 943$ kJ/kg
Two-phase, liquid-dominated	Low-enthalpy	$220\,^{\circ}C < T < 250\,^{\circ}C$	943 kJ/kg $< h <$ 1100 kJ/kg
	Medium-enthalpy	$250\,^{\circ}C < T < 300\,^{\circ}C$	1100 kJ/kg $< h <$ 1500 kJ/kg
	High-enthalpy	$250\,^{\circ}C < T < 330\,^{\circ}C$	1500 kJ/kg $< h <$ 2600 kJ/kg
Two-phase, vapour-dominated		$250\,^{\circ}C < T < 330\,^{\circ}C$	2600 kJ/kg $< h <$ 2800 kJ/kg

pressure does not drop as much and less boiling occurs. Hence production enthalpies are lower – typically at, or not much above, the enthalpy of hot water at the reservoir temperature.

There is not necessarily a permeability boundary around the whole edge of the hot reservoir, and cold recharge from the sides of the reservoir can easily flow into it from some directions. Typically, vertical permeabilities are also high. As a result, cold recharge may flow down into the reservoir from above or extra hot recharge may flow into the reservoir from below. The balance between hot and cold recharge varies from one system to the next. The common experience of infield injection in this type of geothermal field is that it has caused degradation of the resource by thermal breakthrough and injection has been moved outfield, e.g. Miravalles [9], Ahuachapan [8].

1.2.3. Two-phase, liquid-dominated, medium-enthalpy systems

In their pre-exploitation or natural state these systems contain all, or mostly, very hot water (i.e. the boiling zones are non-existent or small). However, when production wells are drilled, at least some of them discharge at medium enthalpies (usually in the range 1100–1500 kJ/kg). This is because boiling occurs at the feed zones of the wells, as a result of large pressure drops. This situation is caused by low reservoir permeability, often resulting from a few large fractures within a "tight" rock matrix.

The permeability in the rock surrounding the hot reservoir in such systems may be similar to that inside the reservoir, i.e. there is not necessarily any permeability contrast between the inside (the hot part) and outside (the cold part) of the reservoir.

The distinguishing feature between this type of system and the low-enthalpy liquid-dominated systems discussed in the previous section is the level of fracturing. The medium-enthalpy version (e.g. Mokai [19]) typically has a few major fractures whereas the low-enthalpy versions (e.g. Wairakei [20]) have more general fracturing and more widely spread permeability.

In two-phase medium-enthalpy systems, the boiling zones that develop as a result of production are typically localized and have a high steam fraction. The steam fraction may increase during production, and in some cases a localized vapour-dominated zone may develop. In low-enthalpy liquid-dominated systems, by comparison, the boiling zones are large in extent and are "wet", i.e. they have a low steam fraction.

The large pressure drop at production wells and the boiling induced in the reservoir are not undesirable effects from a reservoir engineering point of view. A medium-enthalpy mixture of water and steam is desirable because the conversion of thermal energy to electricity is more efficient and less separated water has to be dealt with. The drop in reservoir pressure may result in some subsidence [21], a reduction in surface flows in liquid features and an increased surface heat flow, mainly from steam, at some locations.

The pressure drop in the reservoir near the production wells is in practice buffered by the boiling process. The pressure declines rapidly until boiling occurs, and then the pressure declines more slowly. It tracks down the boiling curve following the temperature decline resulting from two processes:

- The heat extracted from the rock matrix boils off the water, turning it into steam.
- The cool recharge (mainly water rather than steam) is attracted to the low-pressure zone both from the top and the sides of the reservoir.

In some cases, hot deep recharge may offset the cool recharge depending on the balance between lateral and vertical permeabilities.

In two-phase medium-enthalpy systems injecting cold water into the production zone will cause faster cooling of the production wells. In some cases, it may even suppress boiling and cause the production enthalpy to drop to that of hot water. This type of system does not run out of water, as is often the case for vapour-dominated systems. Also, these systems do not suffer from excessive pressure decline and do not require pressure maintenance, as is often the case for hot water systems. Therefore, from a reservoir engineering perspective there is no reason to inject infield in two-phase medium-enthalpy geothermal systems. Experience at a number of fields supports this statement. Often injection in two-phase medium-enthalpy geothermal systems has resulted in adverse thermal breakthrough and a consequent move of injection outfield, e.g. Cerro Prieto [22], Tiwi [7].

1.2.4. Two-phase, liquid-dominated, high-enthalpy systems

These systems are very similar to the medium-enthalpy category discussed above. They also consist of few major fractures in a low permeability matrix but in this case the volume and/or the permeability of the fractures are somewhat smaller and the boiling zones surrounding the production wells are dryer and thus the production enthalpies are in a higher range, say 1500–2600 kJ/kg. In this case natural recharge is limited by low permeability and some infield reinjection may be beneficial.

1.2.5. Two-phase, vapour-dominated systems

By their very nature, vapour-dominated two-phase systems have low permeability in the reservoir zone and very low permeability surrounding the reservoir. If this were not the case, cold water would flow into the low-pressure vapour-dominated reservoir from the surrounding cool rock. As the pressure decreases in this type of geothermal system during production, more and more of the immobile water boils to form steam which then flows towards the production wells. Thus the water in a vapour-dominated reservoir is not replenished by natural recharge and, after some years of production, parts of the reservoir may run out of immobile water and become superheated (i.e. the temperature of the steam is above the boiling point). In this case it is beneficial to inject water directly above the depleted reservoir and close to the production wells. In some cases, extra water as well as the steam condensate has been injected. This strategy has been successfully followed at, for example, The Geysers in California [15] and Larderello in Italy [23].

1.3. Location of injection wells

The location of injection wells relative to production wells is probably the most important issue in the design of a reinjection system. In this paper *infield reinjection* refers to injection wells located close to the production wells and within the hot part of system – say within the resistivity boundary. *Outfield reinjection* refers to the injection wells further away from the production wells and outside the hot part of system. Unfortunately these definitions are not precise and distances cannot be given definitively.

Some authors (e.g. SKM [14]) have attempted to define *infield reinjection* and *outfield reinjection* in terms of how well the injection wells and production wells are connected, measured by pressure communication. However this classification requires information that is not usually available, particularly before the injection wells are drilled, and therefore may not be practically useful.

2. Information available

Reports and articles, available in the open literature, on 91 geothermal fields were reviewed. In each case we were seeking

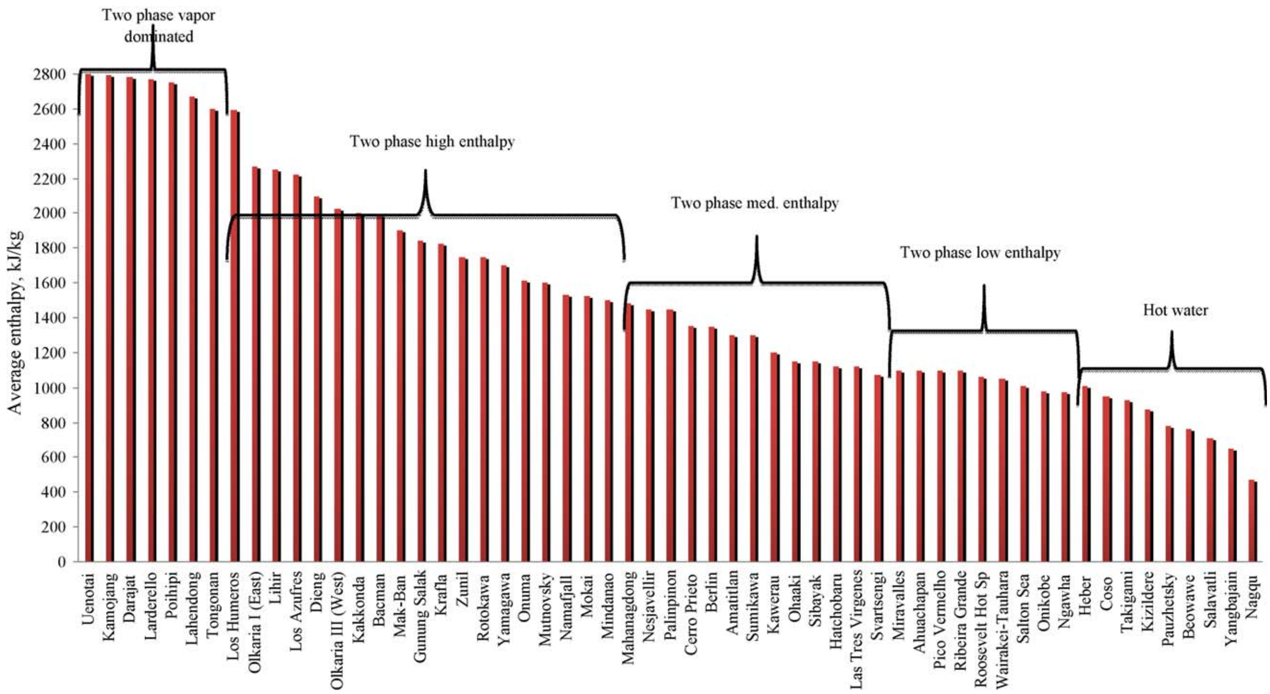


Fig. 1. Average enthalpy value for each field and their classification.

information about the current power generation, total mass production, average production enthalpy, location and amount of reinjection and any problems associated with production and reinjection. Table A.1–Table A.6 (see appendix) summarize the information obtained from this survey. In many cases the information available is incomplete and the summary plots given below are based on fewer than 91 fields.

The average enthalpy value for each geothermal field and the classification of the fields are shown in Fig. 1.

Fig. 2(a) and (b) present the data in pie-chart form for total energy production (MWe) and bar chart form for mass production per MWe for each type of geothermal system. According to Fig. 2(a) currently 55% of the geothermal power comes from the combination of two-phase liquid-dominated high-enthalpy systems and two-phase vapour-dominated systems. Two-phase liquid-dominated medium-enthalpy systems also make a significant contribution compared to the low-enthalpy and hot-water systems. Since they contain a lower energy density than high- and medium-enthalpy systems, hot-water and two-phase liquid-dominated low-enthalpy systems require higher rates of mass production per unit MWe of power (Fig. 2(b)).

It should be noted that because of the incompleteness of the information Fig. 2(a) represents the data from 82 fields out of the 91 total (99.7% according to energy production) and Fig. 2(b) represents data from only 62 fields (84.5% according to energy production).

Some compromises were required in preparing the data shown in the plots, e.g. power production from the Darajat field increased from 145 MWe to 259 MWe in 2007. Since the only available recent mass production data is from 2005, in Fig. 2(b), the power production value of year 2005 (145 MWe) was used. However in Fig. 2(a), the most recent power production data (259 MWe) was used for this field.

Fig. 3(a) and (b) presents the reinjection data in pie-chart form for total reinjection and bar chart form for reinjected mass per MWe, respectively. As expected the hot-water and two-phase, liquid-dominated, low-enthalpy systems require the injection of large amounts of water while two-phase vapour-dominated systems have the lowest percentage of total reinjection. For the contribution of vapour-dominated systems in Fig. 3(a) and (b) additional surface water reinjection (for Darajat, Larderello and The Geysers) has been included in the charts.

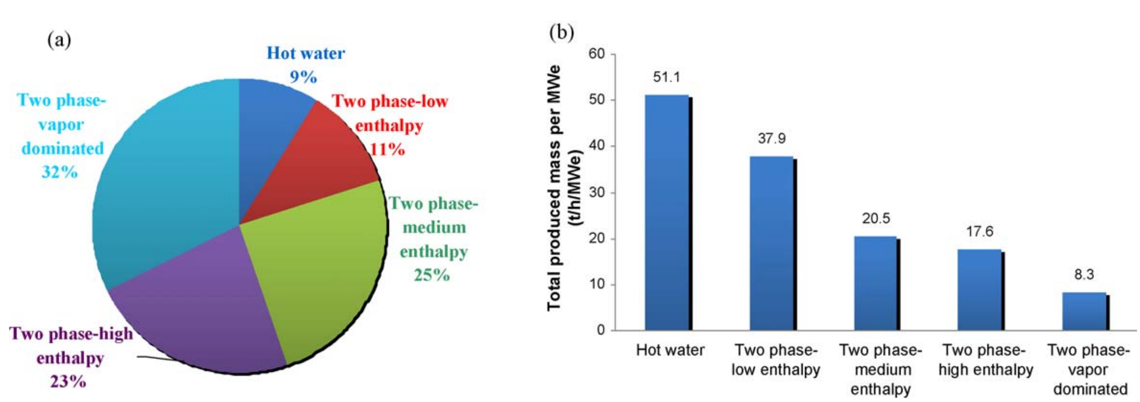


Fig. 2. (a) Total energy production, MWe and (b) total mass production (t/h) per MWe for each type of geothermal system.

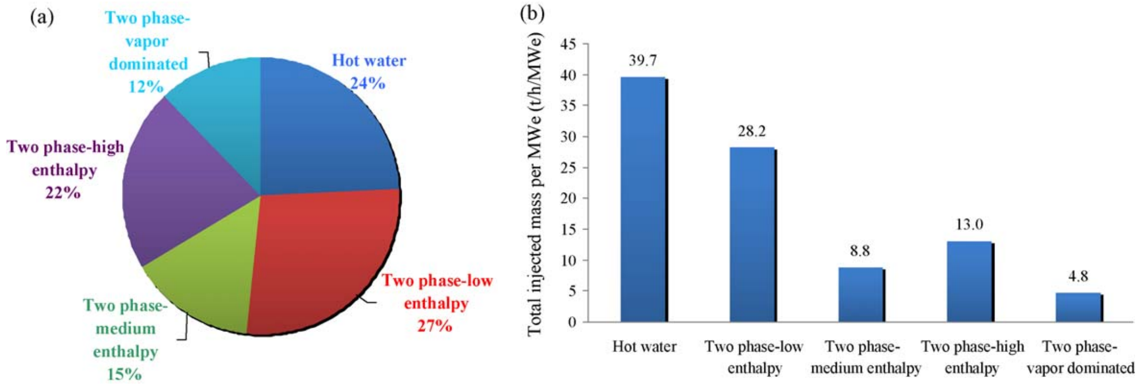


Fig. 3. (a) Total mass reinjection (t/h) and (b) total mass reinjection (t/h) per MWe for each type of geothermal system.

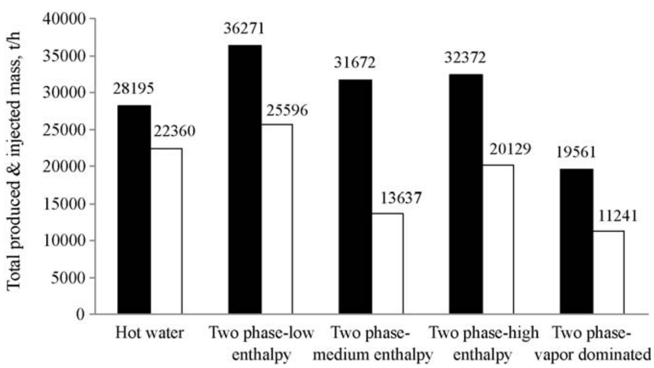


Fig. 4. Total mass production (black) and reinjection (white), (t/h) for each type of geothermal system.(For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)

Fig. 4 shows total mass production (black) and reinjection (white), for each type of geothermal system. Fig. 4 shows that: hot-water systems have the highest percentage (80%) of reinjection of produced mass back into the reservoir, while it is 70% for two-phase liquid-dominated low-enthalpy and 43% for medium-enthalpy. The reinjection fraction of produced mass for two-phase high-enthalpy systems is 62% and for two-phase vapour-dominated system is 57%. Note that the medium-enthalpy reservoirs have the lowest percentage of reinjection of produced mass.

Although the total amount of waste water is less per MWe in two-phase high-enthalpy or two-phase vapour-dominated systems than the other systems, reinjection is more common in these types of fields. It should also be noted that additional surface water reinjection was carried out in a few vapour-dominated fields (Darajat, Larderello and the Geysers) see Fig. 4.

Because of the lack of information available about the amount of reinjection in many of the fields among the 91 considered Figs. 3 and 4 represents the data from only 54 fields (82.2% according to energy production).

Fig. 5 presents mass produced per MWe generated for the individual fields, grouped according to their enthalpy classification. The results are affected somewhat by the individual characteristics of the field but the general trends are clear. The fields that produce high enthalpy fluids require less fluid (ton/hr) per MWe.

Fig. 6 shows the mass of reinjected fluid for each field per MWe produced, again grouped according to the enthalpy classification.

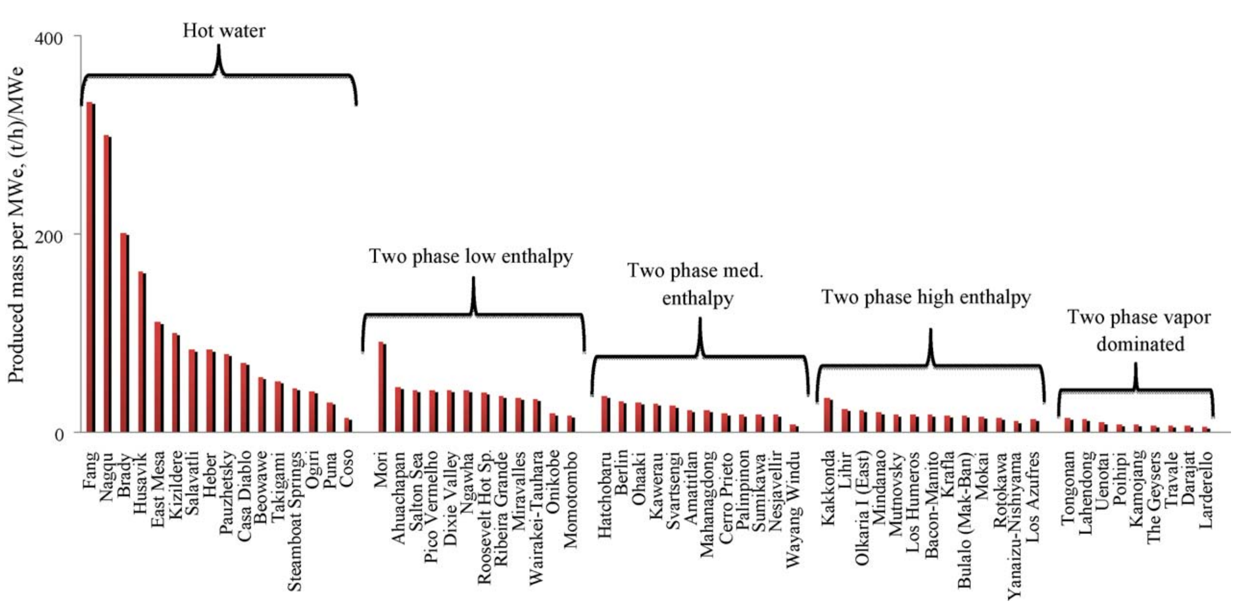


Fig. 5. Produced mass per MWe energy generated for each field.

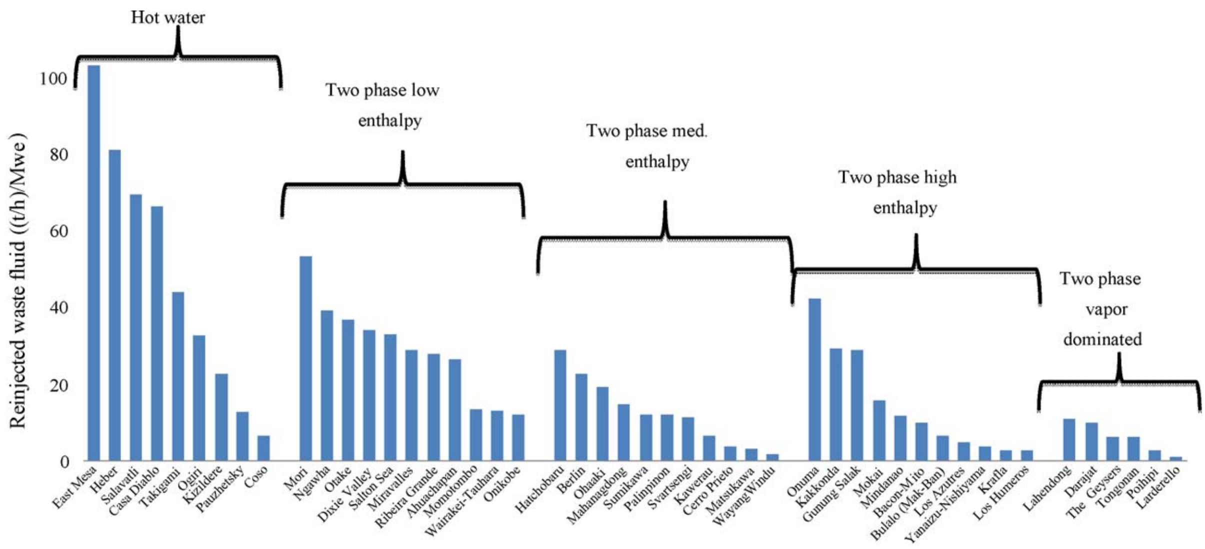


Fig. 6. Mass reinjected per MWe.

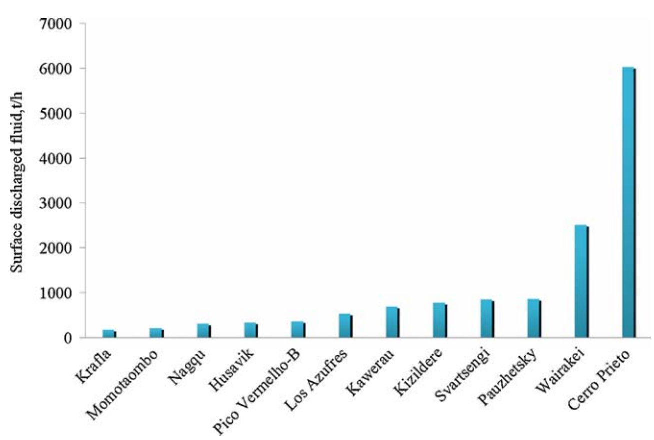


Fig. 7. Waste water discharged to the surface.

This figure also includes the additional surface water reinjected at Darajat, Larderello and The Geysers. As expected the results show that fields which produce high enthalpy fluids reinject smaller amounts of fluid per MWe.

Fig. 7 shows the amount of waste water discharged to the surface from 12 fields for which data are available. For some of these fields, the amount of waste water discharged to the surface is not given in the literature. Instead of this, steam and brine production flow rates and percentage of surface discharge of total produced fluid is given. For this type of data, waste water discharge was calculated to obtain the points plotted in Fig. 7. In these calculations, we simply assumed that the total production rate is equal to the total waste fluid for hot-water reservoirs. However for two-phase reservoirs the waste water rate was taken to be the sum of produced total brine rate and 10% of the produced total steam rate assuming that 90% of the condensate is typically evaporated through the cooling towers into the atmosphere. This assumption is based on the reported data which shows that steam losses vary between 75 and 90% (e.g. Ahuachapan about 90%, Mori about 87%, Miravalles about 82% and The Geysers about 75%).

3. Summary of reinjection experience

In this part of the paper the review of worldwide reinjection experience is summarized in order to provide a qualitative understanding of worldwide reinjection strategies and the response of different type of geothermal reservoirs to these strategies. For this summary, the location and amount of reinjection, and problems and benefits associated with reinjection, particularly the effect on production, are discussed.

(i). In *two-phase*, *vapour-dominated reservoirs* infield reinjection is usually used and very few adverse effects on the thermodynamic state of the reservoir have been reported. In some cases injection has had an important role in maintaining steam production (e.g. Kamojang [24], Larderello [25], Poihipi [26]). The Geysers field has been affected thermally with temperature and wellhead enthalpy declines being observed. But overall infield reinjection has assisted steam production. Recently additional make-up water has been added to the reinjection [27] and this has significantly slowed the decline in steam production.

(ii). In *two-phase*, *liquid-dominated*, *high-enthalpy reservoirs* mostly infield reinjection is used. Thermal breakthrough had been observed in Olkaria 1 [28], and Bulalo [12] but when the infield reinjection was stopped or was reduced, the affected wells recovered gradually. Chemical breakthrough has been observed in Krafla [29] and Los Azufres [30], but no changes have been reported in the thermodynamic conditions in these fields.

(iii). Several of the *two-phase*, *liquid-dominated*, *medium-enthalpy reservoirs* have experienced thermal breakthrough (e.g. Hatchobaru [3,10,31], Matsukawa [32], Sumikawa [33], Cerro Prieto[22,34], Palinpinon [35], Ohaaki [36]) or the precursor chemical breakthrough (e.g. Berlin [37], Tiwi [2], Mahanagdong [38]) resulting from infield reinjection. Moving reinjection wells outfield has resulted in the recovery of the production wells.

(iv). Most *two-phase*, *liquid-dominated*, *low-enthalpy reservoirs* have experienced thermal breakthrough caused by infield reinjection (e.g. Miravalles [9], Ahuachapan [8], Mori [13], Onikobe [39,40]). But these fields have recovered when the production–reinjection scheme was changed. Some fields have not been significantly affected by thermal or chemical breakthrough (e.g. Otake [41] and Ngawha [42]). Reinjection returns have been recorded in Dixie Valley field but in this case pressure support from reinjection has helped to

maintain production and infield reinjection has been maintained [43].

(v). Most *hot-water reservoirs* have experienced thermal breakthrough (e.g. Pauzhetsky [44], Kizildere [45], East Mesa [46], Beowawe [47], Brady [18], Empire [48], Steamboat [14]). But infield reinjection has helped with pressure maintenance (e.g. Pauzhetsky [44], Kizildere [45]). Shifting reinjection deeper to avoid temperature declines may cause an increase in the pressure decline (e.g. Casa Diablo [49]). In some cases moving reinjection wells closer to production wells has had a positive effect by reducing drawdown (e.g. Beowawe [47]).

(vi). Full or partial surface discharge is still a common practice in many fields worldwide (e.g. Krafla [3,50], Nesjavellir [51], Svartsengi [51], Momotombo [52], Husavik [53], Kawerau [54], Wairakei [55], Kizildere [56], Cerro Prieto [57], Olkaria I [58], Ohaaki [36], Los Azufres [57], Pico Vermelho [59,60], Pauzhetsky [44], Yangbajain [61], Nagqu [62], Lihir [63], Bouillante [64]). However, currently there is general agreement on the important benefits of reinjection in preventing environmental pollution from geothermal fluids (chemical and thermal), in sometimes providing pressure support to the reservoir and in preventing or reducing subsidence.

(vii). In most cases the adverse effects of reinjection have been reversed when infield reinjection was abandoned or reduced (e.g. Tiwi [7], Ahuachapan [8], Miravalles [9], Hatchobaru [3,10], Uenotai [11], Bulalo [12], Tongonan [65], Palinpinon [17], Onikobe [39], Mindanao [66], Olkaria I [67]. However, long-term adverse effects can be seen in a few fields (e.g. Brady [18], Mori [13]), and to some extent in Mahanagdong [38] (possibly due to reinjected fluid combined with groundwater inflow), where these plants are running at below design capacity after the reinjection was moved outfield. For example, at Brady the temperature and flow rate of the produced fluid decreased after the start of reinjection. After 60% of reinjection was diverted outfield, the fluid production level and temperature did not recover. Similarly at Mori approximately 40% of reinjection was moved outfield but still there are reinjection returns to the production wells and some of the reinjection returns have been replaced by cold recharge from groundwater [13].

(viii). In most cases of long-term infield reinjection thermal breakthrough to production wells has occurred within ten years of service (Ahuachapan [8], Brady [18], Bulalo [12], Coso [68], Hatchobaru [3], Kakkonda [3,14,69], Mahanagdong [38], Matsukawa [4], Mindanao [70], Miravalles [9], Mutnovsky [71]) Palinpinon[17], Pauzhetsky [44], Sumikawa [33], Uenotai [11], The Geysers [15], Tiwi [7], Tongonan [65], Krafla [29], Mori [13], Ohaaki [36], Onikobe [39], Empire [48], East Mesa [46], Casa Diablo [14], Olkaria I [34], Los Humeros[72], Dixie Valley [43], Kizildere [45]). The other cases where infield reinjection has not yet causing any thermal breakthrough may be because reinjection has not been running for long enough (Amatitlan [73], Rotokawa [74], Mokai [75], Ngawha [76], Berlin [37], Zunil [77], Salak [78], Ribeira-Grande [60], Dieng [79], Wayang-Windu [80], Los Azufres [30], Ngawha [76]) or the amount of reinjected fluid is very small (Larderello [81], Cerro Prieto [22,34], Kamojang [82], Darajat [83], Krafla [3,50], Nesjavellir [84,85], Svartsengi [3], Kawerau [86]).

(ix). Infield reinjection is a cheap but often temporary method of waste fluid disposal. It is normally undertaken to reduce costs during early stages of field development (Rotokawa [74], Mokai [87], Ahuchapan [8], Salak [88], Zunil [77], Ngawha [89], Amatitlan [73], Brady [18]) or as a first step in a full scale reinjection strategy in existing developments (Cerro Prieto [22,34], Matsukawa [3,4,32], Tiwi [7], Wairakei [90], Olkaria [28], Ohaaki [36], Kawerau [54], Pauzhetsky [44], The Geysers [91]). In most cases existing production or investigation wells were used for reinjection at first, and these wells were usually located in the middle of the field (Rotokawa [74], Mokia [92], Ahuchapan [8], Salak [78], Zunil [77], Ngawha [42], Amatitlan [73], Cerro Prieto [22,34], Matsukawa [4], Tiwi [7], Wairakei [90], Olkaria [67], Pauzhetsky, The Geysers [91], Brady [18]). Reinjection in these wells was abandoned or reduced when the adverse effects of infield reinjection became evident (Ahuchapan [8], Tiwi [7], Salak [78], Matsukawa [4], The Geysers [15], Bulalo [12], Tongonan [65], Mahanagdong [38], Brady [18], Rotokawa [74]).

(x). Full reinjection has been achieved in some existing reservoirs (e.g. Ahuachapan [93], Tiwi [7], Ogiri [94], Takigami [95], Coso [96], East Mesa [97], Heber [98], Puna [99], Soda lake [100], Steamboat springs [101], Mori [13], Ngawha [87], Salton Sea [102], Mahanagdong [38], Zunil [77], Salak [78,88], Mt. Amiata [103], Onuma [14,104], Yamagawa [105], Los Azufres [57], Los Humeros [57], Mokai [106], Rotokawa [75], Mutnovsky [14,107], Mindanao [70], Darajat [83], Kamojang [24], Poihipi [26], Tongonan [17], The Geysers [91]). Some other fields (Cerro Prieto [22,34], Wairakei [90], Olkaria [34] are in the process of decreasing surface discharge by greatly increasing reinjection but may not achieve full reinjection.

(xi). A reinjection scheme that provides pressure support to the reservoir (infield reinjection) requires a careful monitoring program to prevent reservoir cooling. Cooling can be reversed if mitigation measures are taken promptly.

(xii). Shallow reinjection can result in increasing flux of fluid to the surface affecting existing natural features (e.g. Rotokawa [74], Mokai [75], Tongonan [108], Kawerau [54], Dixie Valley [43]) and may help create new features (e.g. Rotokawa [74], Dixie Valley [43]) fed directly or indirectly from the injected fluid. In some fields shallow reinjection resulted in ground inflation (e.g. Heber [3], Mokai [109], Steamboat Hills [110]). These effects are not desirable if they take place within residential areas, agricultural activity areas or within industrial areas. Therefore, shallow reinjection should be planned with caution.

(xiii). An excessive reinjection pressure may make pumping uneconomical (Heber [2]) or operationally unfeasible if it exceeds the design pressure of the surface equipments (pipes, valves etc.). An excessive reinjection pressure can also cause hydro-fracturing or induced micro-seismic activity (The Geysers [111]).

(xiv). For some cases where the cap rock is fractured or is not continuous reinjection supports the reservoir pressure and prevents cold groundwater inflow (Namafjall [112], Mori [13]). Shifting reinjection to deeper parts of the reservoir to prevent returns and a temperature decline may introduce a pressure decline (Casa Diablo [14]). In one case moving injection wells toward the production wells has had a positive impact by reducing drawdown (Beowawe [47]).

(xv). The optimum total reinjection strategy for hot-water and liquid-dominated two-phase reservoirs (low-enthalpy and medium-enthalpy) appears to be a mix of infield and outfield reinjection. The infield reinjection provides pressure support to the main bore field and reduces drawdown, groundwater

inflow and subsidence. The outfield reinjection reduces the effect of thermal breakthrough. The proportion of infield to outfield injection flow rates is case specific and typically the infield reinjection rate needs to vary with time as a part of the steam field management strategy.

(xvi). Experience (e.g. at Ohaaki [113] and Wairakei [114]) has shown that the reinjection pressure (well head pressure) may reduce and the well injectivity may increase with reduction in the temperature of the reinjected fluid. This is likely to be related to the higher density of the colder water resulting in high hydrostatic pressure on the injection zone. Also cooling results in shrinkage of the reservoir rock and expansion of fractures thus improving the permeability and reducing injection pressure needed at the surface. However, cooling the waste geothermal brine results in super saturation of the brine with amorphous silica which causes major scaling and deposition. It also requires: large cooling/holding ponds, additional infrastructure, pumping power and present more environmental risk from contamination of shallow ground water aquifers and water ways.

4. Concluding remarks

This review shows that, the response of the reservoir to the various reinjection strategies is strongly dependent on the type of geothermal system. The produced mass flow rate per MWe generated reduces with the increase in enthalpy hence reduce the waste water that needs to be disposed of.

Vapour-dominated systems will require infield reinjection, possibly with a need for supplementary water. Liquid-dominated systems operate best with a combination of infield and outfield reinjection. Excessive infield reinjection can result in thermal breakthrough and reservoir cooling, while outfield reinjection may not provide enough pressure support.

Reinjection is an environmentally friendly method of waste water disposal. It helps with the reservoir recharge, pressure support and can be used to manage subsidence. However careful monitoring is required to prevent reservoir cooling. Surface discharge is still a common practice with several fields only recently moving towards partial or full reinjection.

The choice of the optimum depth of reinjection is difficult. Shallow reinjection can result in contamination of shallow ground water aquifers, but deep reinjection may not provide the required pressure support to the shallow reservoir.

The effects from improper reinjection strategies may not be reversible. Therefore for new fields, reinjection should be planned as early as possible in the field development and should be adapt to possible changes in the reservoir conditions with time.

Acknowledgement

The authors would like to acknowledge Kerin Brockbank from Contact Energy for her valuable assistance during data collection stage of this work.

Appendix A

Tables A.1–A.6.

Table A.1
Hot water reservoirs.

Country	Field	Start date	Current generation, MWe	Total mass produced, t/h	Average enthalpy, kJ/kg	Reinjection Rate, t/h	Reinjection Strategy	Effects of Reinjection	References	Additional notes
China	Langju (Tibet)	1987	2						[115]	Fluid temperature 80–180 °C
China	Nagqu (Tibet)	1993	1	300	470	0	Surface discharge	n/a	[62,115]	Fluid temperature 110–114 °C
China	Yangbajain (Tibet)	1977	24.18		650	~70%	Initially discharged to Zangbu River, in 2002 around 70% infield reinjection into shallow reservoir		[61,115–117]	Output capacity 45.43 MWe and 917.2 kg/s for 31 wells [61]
Iceland	Husavik	2000	2	324		0	Surface discharge	n/a	[14,51,118,119]	Fluid temperature 121 °C. Heat is also used for district heating
Japan	Ogiri	1996	30	1250		975	Total reinjection		[94,120]	Production and reinjection rates are based on 1998 data
Japan	Takigami	1996	25	1270	925	1100	Total outfield injection		[95,120–122]	
Russia	Pauzhetsky (Kamchatka)	1967	11	864	780	140	Partial infield/edgefield reinjection. Reinjection started in 1979, no reinjection between 1988 and 1993	Reinjection helped to restore the mass balance and to support pressures. At early stages of production the enthalpy was ~800 kJ/kg. For some production wells close to reinjection wells enthalpy has decreased by 100–150 kJ/kg	[44,123]	A high production rate caused large changes in enthalpy. As the result of a significant enthalpy drop the northern section of the field was abandoned in 1997. The central section of the field has also suffered a temperature decline
Thailand	Fang	1989	0.18	60		0	Likely to be surface discharge		[116]	The resource is used for greenhouse heating and other direct applications besides provision of power
Turkey	Kizildere	1984	10	1000	875	225	Partial (20%) infield reinjection to the shallow reservoir started in 2002. The remaining brine (80%) is discharged into a river	After 17 months of reinjection cooling was observed at the nearest well and this well was shut in. The production rate was increased from 830 t/h to 1000 t/h	[45,56,124,125]	A report based on a modeling study of the effect of reinjection recommended that the shallow reservoir should be used for reinjection
Turkey	Salavatli	2006	6.5	545	710	450	Infield reinjection (about 1.1 and 2.5 km away from production wells)		[125–127]	Two new production and one reinjection wells are being planned to be drilled for a 10 MWe power plant
USA	Beowawe	1985	16.6	928.8	760		Initially outfield reinjection, reinjection. Iin 1994 it was moved closer to the production wells	A temperature decline has resulted from recharge and reinjection returns. Moving reinjection towards production has had a positive impact by reducing drawdown	[34,47,128,129]	Enthalpy declined from 920 kJ/kg in 1986 to 760 kJ/kg in 2000
USA	Brady	1992	8.8	1772			Initially infield reinjection, 60% of injection was moved outfield by 2001	Reinjection returns occurred during infield reinjection (the temperature declined and tracer returns were observed)	[18,128,130,131]	The temperature of produced fluid was 182 °C in 1992. Initially temperatures in the production wells declined rapidly reaching 162 °C by mid-1993. By mid-1995 the temperature to the plant was 158 °C and trending downward

Table A.1 (*Continued*)

Country	Field	Start date	Current generation, MWe	Total mass produced, t/h	Average enthalpy, kJ/kg	Reinjection Rate, t/h	Reinjection Strategy	Effects of Reinjection	References	Additional notes
USA	Casa Diablo	1985	40	2794		2645	Infield reinjection	Temperature decline was observed. A shift to deeper injection decreased the temperature decline but increased the pressure decline	[14,34,49,102,132,133]	Reservoir temperature is 150–175 °C
USA	Coso	1987	274	4028	840–2800	1814	Total infield reinjection of fluid and gas	After 5–7 years of service, the reinjection rate decreased due to mineral deposition in fractures surrounding the injection wells. Gas breakthrough due to reinjection of gas required additional H_2S abatement systems	[68,96,102,128,134,135]	
USA	East Mesa	1979	79	8776		8134	Total infield reinjection of fluid and gas	Reinjection returns results in cooling of approximately 1 °F per year	[34,46,97,102,136]	For the Ormesa power plants 100% of all produced fluid and gas are injected. Reservoir temperature range from 146 to 182 °C
USA	Empire	1987	4.8				Edgefield reinjection	Initially the temperature declined due to reinjection. Then a program of partial surface discharge was instituted to create a wildlife wetland. Cooler production wells were shut in to allow the plant to operate at full capacity	[48,128,137]	The fluid temperature was initially 137 °C, falling to as low as 114 °C by 1996. The dehydration plant is supplied with 168–252 t/h of geothermal fluid at a minimum temperature of 141 °C
USA	Heber	1985	85	7044	1010	6877	Total infield/edgefield reinjection	Ground inflation has been reported in the reinjection sector	[2,3,98,102,128,138]	Reinjection from a 47 MWe unit has caused ground inflation
USA	Puna (Hawaii)	1984	30	907			Total infield injection of fluid and gas. Reinjection was carried out deeper than the feed zones in the production wells	No reinjection returns have been reported. Severe external casing corrosion by acidic geothermal fluid was reported. Reinjection capacity decreased	[68,99,128,139]	
USA	Soda Lake	1987	26.1				Total reinjection of the waste fluid		[100,128]	In 1989 a 3.6 MWe binary plant used about 182 t/h at 182 °C, with total reinjection of waste fluid
USA	Steamboat Springs	1986	31	1370			Total infield reinjection. Production and injection use the same shallow aquifer	Tracer tests show that most of the injected water remains within the well field. An average temperature decline of 1 °C per year has been measured	[14,34,101,128,140]	The average fluid production temperature was 160 °C in 1999. Physical constraints prevent the relocation of reinjection wells away from the production wells
USA	Steamboat Hills	1988	14.4			85–95% of production rate	85–90% infield reinjection	Reinjection water is mixed with the municipal domestic water	[101,110,128]	The reservoir temperature is 170–220 °C
USA	Stillwater	1989	21						[128]	

Table A.2
Two-phase, low-enthalpy reservoirs.

Country	Field	Start date	Current generation, MWe	Total mass produced, t/h	Average enthalpy, kJ/kg	Reinjection rate, t/h	Reinjection strategy	Effects of reinjection	References	Additional notes
Costa Rica	Miravalles	1994	162.5	5556	1100	4700	From 1994 to 1998 there was infield injection from the west and edgefield from the south. From 1998 to 2000 reinjection from the west decreased and from the south increased. During 2000–2002 injection was re-directed to the south. In late 2002 a portion of the water injected in the south was diverted back to the western sector of the field to mitigate the pressure drop	During 1994–1997 reinjection returns were observed with chemical breakthrough but no noticeable thermal breakthrough. In 1999–2002 thermal breakthrough occurred towards the east with the effect of injection coming from the south. Chemical breakthrough was noticed in the central wells too. Relocating the reinjection wells back to western part has had an effect on the f;luid chemistry	[9,141–143]	
El Salvador	Ahuachapan	1975	60-65	2818.8	1100	1656	From 1976 until November 1982 an average 25-30% of the extracted fluid was injected infield. Surface discharge + partial outfield reinjection 1982-2004. Total outfield reinjection from 2004.	Infield reinjection caused thermal breakthrough. Wells recovered when infield reinjection was stopped. Outfield reinjection ($>$ 4 km from production area) required pumps	[1,8,93, 144–146]	Total mass production capacity is 2818.8 t/h for 55 MWe
France	Bouillante, Guadeloupe	1987	14.7			N/A	Surface discharge	N/A	[64,116]	Reservoir temperature is 250 °C
Japan	Mori	1982	22.5	2050		1200	Total Infield reinjection from 1982 to 1985. From 1986, 500 t/h of the reinjection fluid was moved further away from the production wells, and deeper production wells were introduced. From 1991 the production zone was decentralized. The production and reinjection zones were relocated giving a much larger separation distance. Currently the waste fluids are injected infield and outfield	Reinjection returns appeared 1 year after the start of the production. Changes in production injection scheme from 1986 reduced the returns but accelerated the pressure decline, which caused the inflow of shallow ground water and a decrease in the enthalpy of the produced fluid. Due to the enthalpy decline, three wells stopped production in 1987–1988. Modifications from 1991, led to a gradual recovery of production but still there are reinjection returns	[13,120]	Reservoir temperature is 230–250 °C The reinjected water, which returns to production wells, with thermal recovery, is now estimated to be about 110 t/h, based on results of the tracer tests
Japan	Onikobe	1975	12.5	241	980	150	Infield reinjection. New reinjection techniques have been applied for acidic and neutral fluids	The enthalpy declined between 1975 and 1985 because of the lack of and the decline in reservoir temperatures caused by local reinjection. Moving production wells deeper zones has stopped the enthalpy decline	[14,39,40, 120]	Separated liquids from acidic wells are expanded to atmospheric pressure and then injected. Separated neutral fluids are maintained at high pressure and reinjected under positive wellhead pressure, to maintain temperature and keep the silica in solution
Japan	Otake	1967	12.5			460	Surface discharge from 1967 to 1971. Total Infield reinjection from 1971	No Reinjection returns	[1,14,41,120]	Reservoir temperature is 200–230 °C 680 t/h injection in 1980 (175 t/h exported by Hatchobaru, (Horne, [1]))

Table A.2 (*Continued*)

Country	Field	Start date	Current generation, MWe	Total mass produced, t/h	Average enthalpy, kJ/kg	Reinjection rate, t/h	Reinjection strategy	Effects of reinjection	References	Additional notes
New Zealand	Ngawha	1997	10	416.67	975	391.6	Total infield reinjection	Reinjection returns. No information on thermal breakthrough	[42,76,87,89,147]	
New Zealand	Wairakei-Tauhara	1958	190	6250	1050	2500	Initially infield, currently partial infield/edgefield reinjection. 50% of water is discharged into a river Over the last 45 years of production, only a small amount water has been reinjected. Most of the reinjection has occurred over the last 10 years	Reinjection returns observed during tracer tests	[55,90,148,149]	
Nicaragua	Momotombo	1983	77.5	1293		1032.6	83% infield reinjection		[52,150]	
Portugal	Pico Vermelho	1980	10	421.56	1100	N/A	Surface discharge	Not applicable	[59,151,152]	100% reinjection is planned after a 10 MW power plant is constructed
Portugal	Ribeira Grande	1994	12.44	452.4	1100	334.1 t/h brine + condensate	1994–1998 surface discharge. From 1998 total infield reinjection		[59,60,151]	334.1 t/h brine 118.3 t/h steam
USA	Dixie Valley	1988	62	2600		2100	Reinjection started in 1988. Infield reinjection is made to the shallower and deeper zones	Reinjection returns have been recorded but no cooling. There is good pressure support from reinjection	[14,34,43]	
USA	Roosevelt Hot Springs (Utah)	1984	26	1043	1065		Infield reinjection		[128,153]	
USA	Salton Sea	1982	336	14172		11060	Total injection (some injection wells are infield)		[102,128,138,154]	Reservoir temperature ranges 290–310 °C

Table A.3
Two-phase, medium-enthalpy reservoirs.

Country	Field	Start date	Current generation, MWe	Total mass produced, t/h	Average enthalpy, kJ/kg	Reinjection rate, t/h	Reinjection strategy	Effects of reinjection	References	Additional notes
El Salvador	Berlin	1992	56	1768	1348	1260	Total Infield reinjection started in 1999. Reinjection occurs in two ways: hot injection into the deep reservoir and shallow aquifer and cold injection into the shallow aquifer	Reinjection returns are indicated by the chemistry. There is no thermal breakthrough	[37,155–159]	In 1999 2× 5 MWe wellhead unit replaced by a 2× 28 MWe power plant
Guatemala	Amatitlan	1998	5	110	1300		Infield reinjection		[73,160]	
Iceland	Nesjavellir	1990	90	1584	1450		Surface discharge with partial infield reinjection. Unused brine is discharged into the shallow boreholes or the stream. Condensed steam and cooling water are also discharged into shallow wells	There is no report of reinjection returns. Initially the average enthalpy was 1700 kJ/kg, but it has decreased slowly to 1450 kJ/kg due to the exploitation of the field. Presently the enthalpy is rising again	[3,51,84,85, 161–163]	Electricity production started 1998. Heat from wastewater is also used for district heating.
Iceland	Svartsengi	1977	45	1188	1075	504	Reinjection started in 1983 and continued intermittently until 2002 at a maximum of about 10–15% of the total produced fluid. After 2002 30–35% was reijected infield, and remainder discharged to the surface	Injection diminished the pressure decline. Cooling of one production well was observed during moderate injection between 1984 and 1988. Cooling in the well reached a maximum (8 °C) in 1989	[3,51,164–168]	Waste brine is also used for direct use applications
Indonesia	Sibayak	2000	2		1150		Infield reinjection		[169–172]	Reservoir temperature is 240–275 °C. Generation was increased to 12 MWe in 2008
Indonesia	Wayang Windu	1999	110	830		830	Infield reinjection		[14,80,169,170]	Reservoir temperature is 250–270 °C Reinjection rate: 730 t/h condensate + 100 t/h brine
Japan	Hatchobaru	1977	70	2556	1125	1368	Total infield reinjection from 1977. Reinjection wells were moved 500 m from the nearest production wells in 1992	Reinjection returns caused a temperature drop (11 °C) in some wells. This caused gradual decline in productivity. Wells recovered once the reinjection was moved further out	[3,10,31, 120,173]	
Japan	Matsukawa	1966	23.5	201*		70	Infield reinjection is used. Since 1988 the condensate and river water have been injected	There have been reinjection returns, and some decrease in enthalpy. Originally it was producing superheated steam but after reinjection started half of the production wells started to produce saturated steam	[3,4,32,120]	Reservoir temperature is 260 °C
Japan	Sumikawa	1995	50	905	1300	condensate + 565 t/h brine	Infield reinjection is used. Currently reinjection is being moved outfield and into deeper formations	Reinjection returns in a few wells has caused a temperature decline	[14,33,120,174]	Enthalpy has decreased gradually from 1600 to 1300 kJ/kg
Mexico	Cerro Prieto	1973	720	13915	1350	2625	Initially there was total discharge into a large evaporation pond. Partial infield reinjection started in 1989.At first injection was into shallow wells but was later switched to deeper zones. Currently there is 80% surface discharge and 20% infield reinjection	There have been reinjection returns in the wells close to reinjection area with chemical and thermal breakthrough	[22,57]	

Table A.3 (*Continued*)

Country	Field	Start date	Current generation, MWe	Total mass produced, t/h	Average enthalpy, kJ/kg	Reinjection rate, t/h	Reinjection strategy	Effects of reinjection	References	Additional notes
Mexico	Las Tres Virgenes	2001	10		1120		Infield reinjection is used		[57,175,176]	
New Zealand	Kawerau	1957	45	1310	1200	300	There is approximately 30% infield injection. Also there is discharge to the Tarawera river and edgefield injection	There are no reinjection returns	[54,86,87,147, 177–179]	Reinjection started in 1991. The reinjection rate was 25%. After KA39 was drilled reinjection was increased to 30%. 690 t/h is discharged into the Tarawera river. A new 90 MWe double flash unit was added in 2008. For the new development 100% of spent fluids are injected into 2500 m deep wells at the NE margin of the field
New Zealand	Ohaaki	1988	46.7	1400	1150	890	At early times of production there was infield and outfield reinjection. Currently outfield and edgefield reinjection are used	Reinjection returns from infield injection were observed. To minimize potential damage to the resource infield reinjection was stopped and edgefield and outfield reinjection wells were commissioned	[36,180,181]	
Philippines	Mahanagdong	1997	198	4300	1481	2900	There is total infield and edgefield reinjection. The current policy is to move reinjection further from the production wells	Rapid drawdown caused cool recharge and reinjection returns. After a serious enthalpy drop in some wells the injection practice was revised and thermal recovery was observed	[38]	
Philippines	Palinpinon	1983	192.5	3500	1450	2300	There was infield reinjection from 1983 to 1989. In 1989 outfield reinjection was adopted and infield reinjection was reduced	Reinjection returns resulted from infield reinjection. Wells recovered after infield reinjection was stopped and injection was relocated further out	[17,35,182]	
Philippines	Tiwi	1979	330				Surface discharge occurred from 1979 to 1983 and partial infield reinjection from 1983 to 1986. Partial edgefield reinjection 1984. Currently total outfield and edgefield reinjection	Reinjection returns resulted from infield reinjection. Excessive infield reinjection caused the collapse of the steam saturation and a sudden loss of productivity from some wells. The wells recovered once infield reinjection was phased out	[7,183]	Reservoir temperature is 320 °C

Table A.4
Two-phase, high enthalpy reservoirs.

Country	Field	Start date	Current generation, MWe	Total mass produced, t/h	Average enthalpy, kJ/kg	Reinjection rate, t/h	Reinjection strategy	Effects of reinjection	References	Additional notes
Guatemala	Zunil	1999	24		1750		Total infield injection		[77,160]	
Iceland	Krafla	1977	60	986.4	1825	175	About half of the effluent is being reinjected infield. The other half is discharged to the surface	There have been reinjection returns shown by tracer tests	[3,29,50,51,184]	
Iceland	Namafjall (Bjarnarflag)	1969	3		1532	N/A	The effluent is discharged into a pond but then seeps into the lava field	N/A	[29,51,112,184]	Steam is also used for industrial applications. For wells N-11 and N-12 the enthalpy was about 2300 kJ/kg in 1982. It subsequently declined and was 1700–1850 kJ/kg in 1997, showing the effect of cold water recharge
Indonesia	Dieng	1994	60		2095		Infield injection is used		[79,169,170]	A recent development (commissioned in 1998)
Indonesia	Gunung Salak	1994	330	11520	1842	9540	There is total infield reinjection	During the initial operation of units 1 and 2, slug tracer and geochemical monitoring confirmed rapid returns of brine to the production wells located 1 km away. Therefore, the injection wells were converted to producers as part of the expansion strategy	[78,88,169,185]	A recent development (commissioned in1997)
Italy	Mt. Amiata	1962	111.5				Total Infield reinjection was used almost from the beginning of exploitation		[103,186]	The reservoir temperature is 300–350 °C. Serious acceptability problems with local communities are slowing down the full exploitation of the project
Japan	Kakkonda	1978	80	2750	2000	2330	During the first 13 years total shallow infield reinjection was used. Then additional injection wells were drilled about 1.5 km away from the production area	Reinjection returns (tracer returns and thermal breakthrough) caused significant cooling of the reservoir and a reduction of the mass flow rate	[3,14,69,120, 187,188]	From 1978 until 1990, with a plant of only 50 MWe the average production was 2990 t/h and injection was 2626 t/h
Japan	Onuma	1974	9.5	540	1613	400	There is total shallow infield reinjection		[14,104,120,189]	
Japan	Yamagawa	1995	30		1000–2400		Total injection is used. To keep the production and reinjection zones separate, the completion intervals for the production wells range from about 1400 to 2100 m, whereas the depth of the reinjection zone is between about 800 and 1200 m depth. Separated water is divided into two hot-water lines (neutral and acidic water) and reinjected in order to avoid precipitation of silica scale		[105,120,190]	
Japan	Yanaizu-Nishiyama	1995	65	750		250	Infield injection is used		[94,120,191]	The reservoir temperature is 270–320 °C. Production and reinjection rates are based on1998 data

Table A.4 (*Continued*)

Country	Field	Start date	Current generation, MWe	Total mass produced, t/h	Average enthalpy, kJ/kg	Reinjection rate, t/h	Reinjection strategy	Effects of reinjection	References	Additional notes
Kenya	Olkaria I	1981	45	1023	2270		Surface discharge is used with partial infield reinjection. In 2002 10% of the total brine was being reinjected. Most of the geothermal wastewater is disposed off by deep reinjection. Cold and hot reinjection have been tried	Be cause it was causing an enthalpy drop, cold reinjection was stopped and the affected wells started recovering. Hot reinjection of separated brine has been going on since 1995. Hot brine reinjection results in an improvement in production wells without causing excessive enthalpy decline	[28,58,65,67, 192–194]	
Kenya	Olkaria III (West)	2000	12		2025		Infield reinjection is used		[6,58,194]	
Mexico	Los Azufres	1982	188	1873	2220	891	Total infield reinjection is used with 50% of the total produced fluid being injected	There has been chemical breakthrough at the production wells close to the southern reinjection zone. There are no report on changes in thermodynamic conditions	[30,57,195]	280 t/h waste water are sent to the binary cycle units before being sent to the injection system
Mexico	Los Humeros	1990	35	627.6	2595	102	Total infield reinjection is used	The reservoir temperature decreased in the southern zone of the field where intensive reinjection takes place	[57,72,175, 196,197]	
New Zealand	Mokai	2000	55	844	1525	condensate + 860 t/h brine	There has been total infield reinjection from the beginning of production	There are no reinjection returns	[75,87,92,106, 109,147,198,199]	The steam flow rate is 308 t/hr, the NCG flow rate 4 t/hr
New Zealand	Rotokawa	1997	31	443	1750		Total infield reinjection into shallow zones is used	There is no report of reinjection returns	[14,74,75,87,200]	
Philippines	Bacon-Manito (Bacman)	1993	150	2590	1990	1494	Infield and edgefield reinjection are used	There are no reinjection returns	[183,201]	
Philippines	Bulalo (Mak-Ban)	1979	425.73	6901	1900	2812	Initially total infield reinjection was used. Presently there is edgefield injection of the total condensate and 60% of the total brine	Infield reinjection returns caused thermal breakthrough. Reduction of infield reinjection resulted in gradual recovery in many wells	[12,183,202]	
Philippines	Mindanao	1996	108.48	2160	1500	1260	There is mixed infield and outfield reinjection of all waste fluid. Recently a recommendation was given to change to outfield reinjection	Reinjection returns was detected in 1998. Increase in mass extraction caused thermal breakthrough, but when a constant rate of production and reinjection was carried out thermal recovery was observed	[66,70,183,203]	
Papua New Guinea	Lihir	2003	36	830	2250	N/A	Surface discharge	Not applicable	[63,204,205]	
Russia	Mutnovsky (Kamchatka)	1999	62	1118	1600		Total infield reinjection		[14,107,123]	Analysis of the Na/K geothermometer from samples from five principal wells showed that, since exploitation started, temperatures have dropped in some of the production wells (20 °C for well 4E and 4.5 °C for well O29W)

Table A.5
Two-phase, vapour-dominated reservoirs.

Country	Field	Start date	Current generation, MWe	Total mass produced, t/h	Average enthalpy, kJ/kg	Reinjection rate, t/h	Reinjection strategy	Effects of reinjection	References	Additional notes
Indonesia	Darajat	1994	145	907.2	2783	1450*	There is total infield reinjection augmented with surface water and some of the NCG	Tracer testing showed tracer breakthrough in five production wells within 5–12 days	[83,169,172,185,206–208]	Condensed steam + surface water re-injection. Since 2007, the production capacity has been increased to 259 MWe
Indonesia	Kamojang	1982	140	1086	2792		Total infield reinjection is used	Tracer testing showed chemical breakthrough. No cooling effect is reported. There was improved productivity in three production wells in response to reinjection	[24,82,169,172,185]	Since 2007 the production capacity has been increased to 200 MWe
Indonesia	Lahendong	1999	20	264.2	2670	216.5	Outfield injection is used	There are no reports of reinjection returns	[172,185,209,210]	Since 2007 the production capacity at Lahendong has been increased to 40 MWe
Italy	Larderello	1913	542.5	3060	2770	234 t/h condensates + 270 t/h supplementary water	Infield reinjection started in the early 1970s. From 1983 total shallow infield reinjection was used. A supplementary injection program of fresh water started operation in 1994	Reinjection tests showed that deep reinjection did not yield positive results as the reinjected water was not vapourizing in large amounts. Shallow reinjection has been very successful in increasing the reservoir pressure, especially in depleted areas, and in sustaining production. Plant efficiency has been increased due to the reduction of NCGs. No reinjection returns have been reported	[23,81,211]	The amount of condensate and supplementary water reinjected is much less than the total mass produced
Italy	Travale/ Radicondoli	1973	160	1080		N/A	Infield reinjection started in 1979 to decrease pressure drawdown and subsidence, but was only applied for few years and with negligible quantities of condensate water	Not applicable	[23,212,213]	
Japan	Uenotai	1994	27.5	260	2800		Infield reinjection started in 1993.and resulted in reinjection returns and a temperature decrease. To avoid further mixing of waste water with production, the reinjection was moved outfield	After one and a half years there were reinjection returns causing an enthalpy drop in some wells. The wells recovered once the reinjection was moved	[11,214–216]	During infield reinjection the enthalpy dropped from 2800 to as low as 1800 kJ/kg and then recovered when it stopped
New Zealand	Poihipi	1998	25	200	2750	70	Total outfield reinjection is used	No effect has been reported	[26,217,218]	
Philippines	Tongonan (Lyte)	1983	468.5	6850	2600	2850	There was total Infield reinjection at the start of production in 1983. Reinjection was moved outfield during the early years of production	There were reinjection returns from infield reinjection (chemical and thermal breakthrough). Wells recovered once infield reinjection was relocated further out	[17,65,108,183]	The enthalpy increased as a result of a large increase in production, from about 1800 kJ/kg to a dry steam enthalpy of 2700 kJ/kg in Tongonan 1 and Upper Mahiao

Table A.5 (*Continued*)

Country	Field	Start date	Current generation, MWe	Total mass produced, t/h	Average enthalpy, kJ/kg	Reinjection rate, t/h	Reinjection strategy	Effects of reinjection	References	Additional notes
USA	The Geysers [102]	1960	1000	7200		6150	Infield reinjection was used for condensate disposal in the 1970s. In 1997 additional injection of secondary treated waste water 1455 t/h was started. In 2004 tertiary treated water 1750 t/h was injected (but 1450 t/h only in dry spring session)	Thermal breakthrough forced the reduction of the reinjection rate and relocation of some reinjection wells	[3,15,27,91, 128,219]	With the latest recharge project (SRGRP) the mass replacement rate is up to 80%.

Table A.6
Unclassified reservoirs (details not available).

Country	Field	Start date	Current generation, Mwe	Total mass produced, t/h	Average enthalpy, kJ/kg	Reinjection rate, t/h	Reinjection strategy	Effects of reinjection	References
China	Fengshun (Guangdong)	1984	0.3						[115]
China	Huitang (Hunan)	1975	0.3						[115]
Japan	Suginoi	1981	3						[120]
Japan	Hachijyojima	1999	3.3						[120]
Japan	Kujyukannko	1998	2						[120]
Russia	Okeansky (Kuril Islands)	1999	3.4						[123]
Russia	Goryachii Plyazh (Kuril Islands)	2004	2.6						[123]
USA	Desert Peak (Nevada)	1985	12.5						[128]

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